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IGBAJA WATER SUPPLY

Hydrological Studies

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IGBAJA WATER SUPPLY
REPORT ON HYDROLOGY

SUMMARY

The catchment of the Osin lies on the Pre-Cambrian basement complex and its seasonal rainfall depends on the movement of the inter-tropical convergence zone; the flow is therefore highly seasonal without significant dry season baseflow. An isohyetal map based on all records gives a mean rainfall of 1343 mm, and an annual rainfall index was derived from two long-term stations. A ten year river level record exists within the basin, but this record has not been adequately calibrated by discharge measurements. A tentative rating has been used to compute a flow record which has been extended by correlation with annual rainfall and used in a reservoir trial which suggests that the 2010 target demand of 9.0 x 10^6 litres/day could readily be met. Moreover, at the proposed reservoir capacity of 28 million m^3, a further trial suggested that a demand of 100.0 x 10^6 litres/day could be met with a failure rate of about 1%.

We consider that for the spillway design flood the probable maximum flood should be derived from the probable maximum precipitation by the unit hydrograph technique. The design rainfall for an appropriate duration and catchment area was derived from a Meteorological Office Report on "Extreme Rainfall in Western Nigeria", and a severe time profile was chosen. A conservative percentage runoff, approaching 100% for the design rainfall, was based on published data from nearby countries, and a unit hydrograph shape was deduced from the observed time lag of the gauged basin. The design flood, with a peak of 1500 cumecs was derived from the design storm, percentage runoff and unit hydrograph with an allowance for base flow. We consider it essential that this preliminary synthetic estimate should be checked by the collection of rainfall and runoff records from the site.

INTRODUCTION

This report presents our hydrological analysis of the catchment of the Osin river upstream of the proposed dam site at Igbaja. We present a brief description of the study area and its climate. We then discuss our analysis of the available hydrological data and give estimates of reservoir yield. We give some detailed flood estimates for which we have used the Meteorological Office study of probable maximum precipitation on the area immediately to the west.

The study area

The study area includes the catchment of the Osin river, and extends up to 50 km all around the catchment at the dam site. Figure 1 shows this catchment boundary and the location of the raingauges and river gauging stations that are in service.

The whole area, in which the drainage is generally from south to north lies on granitic gneiss of the Pre-Cambrian basement that is exposed in small areas particularly subject to erosion. The northern and western parts of the study area are characterised by gently undulating topography that lies between 400 m and 500 m (1200 to 1500 feet) above sea level. At the south eastern watershed the ground rises sharply to over 650 m (2000 feet) in a ridge of Pre-Cambrian quartzites. The basement has been weathered to a depth of about 10 m and has produced fairly shallow soils which limit the range of soil moisture storage to perhaps 150 - 200 mm. The variation of land use and vegetation in this part of Nigeria is not marked, although a wide range of crops is grown on the cultivated areas.

Climate

The dominant influence on the climate is the seasonal movement of the inter-tropical convergence zone (ITCZ) where the warmer drier air from the north east meets the cooler moister air flow from the Atlantic. Over Nigeria the ITCZ is usually parallel to the lines of latitude throughout its north-south movement so that, apart from local effects due to altitude, the rainfall pattern is largely latitude dependent.

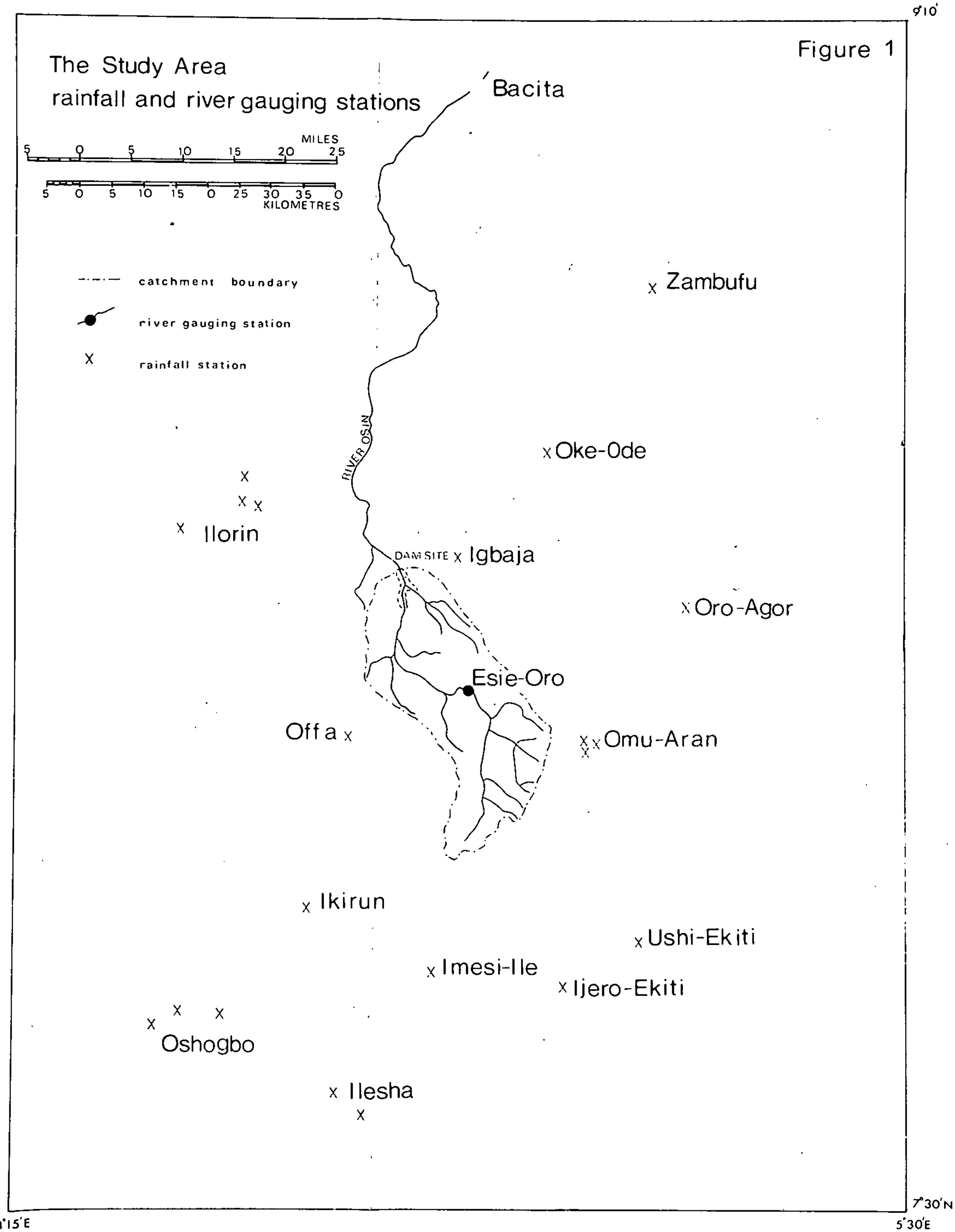

Figure 1
The Study Area
rainfall and river gauging stations
MILES
5 0 5 10 15 20 25
5 0 5 10 15 0 25 30 35 0
KILOMETRES
catchment boundary
river gauging station
rainfall station
Bacita
Zambufu
Oke-Ode
RIVER OSIN
Ilorin
DAM SITE
Igbaja
Oro-Agor
Esie-Oro
Offa
Omu-Aran
Ikirun
Ushi-Ekiti
Imesi-Ile
Ijero-Ekiti
Oshogbo
Ilesha
9°10'
7°30'N
4°15'E
5°30'E

The occurrence of rainfall can be related to the position of the ITCZ at ground level. The zone up to 200-300 km south of the ITCZ is one where the moist air is relatively shallow with dry air above. The occasional rainfall is usually in the form of isolated showers. The main rainfall zone is some 700-1000 km wide and to the south of the first zone. Cumulus cloud is developed and rainfall is substantial. Thunderstorms can give variable and sporadic rainfall over a large area or they can be associated with line squalls moving from east to west. In the southern part of the zone, widespread steady rainfall can develop. South of this main rainfall zone, stable conditions inhibit the upward movement of the moist air and there is little rain.

The effect of the seasonal movement of the ITCZ is illustrated by the rainfall pattern at Offa Railway Station shown in Figure 2. During December to February the ITCZ lies across the study area and rainfall is low. From March to May it is observed that the ITCZ moves slowly north to about $15^{O}N$ (1500 km north of the study area) giving heavier rains prior to the low rainfall of August when the main zone of rainfall lies to the north of the study area. The heaviest rainfall occurs in September and October when the ITCZ moves rapidly southward. Occasionally, this period extends into November, but more often there is a sharp cessation of rainfall in late October, leaving November fairly dry.

This general pattern reported by Griffiths[1] and based on work by Garnier[2] provides a useful framework on which to base our understanding of the seasonal nature of the rainfall. However, variations in the position and speed of movement of the ITCZ from year to year give rise to much variability in rainfall both in time and from place to place. The local nature of storms leads to poor correlation between stations on a daily basis; the annual correlation however is better.

The seasonal pattern of runoff

The river Osin at Esie-Oro is not perennial, as there are no substantial groundwater sources to sustain the flow through the dry season. Generally -

[1] Griffiths, J. F. (ed) Climates of Africa, World Survey of Climatology Vol. 10, Elsevier 1972.

[2] Garnier, J. B. Weather conditions in Nigeria, McGill University, Climatological Res. Ser. 2. 1967.

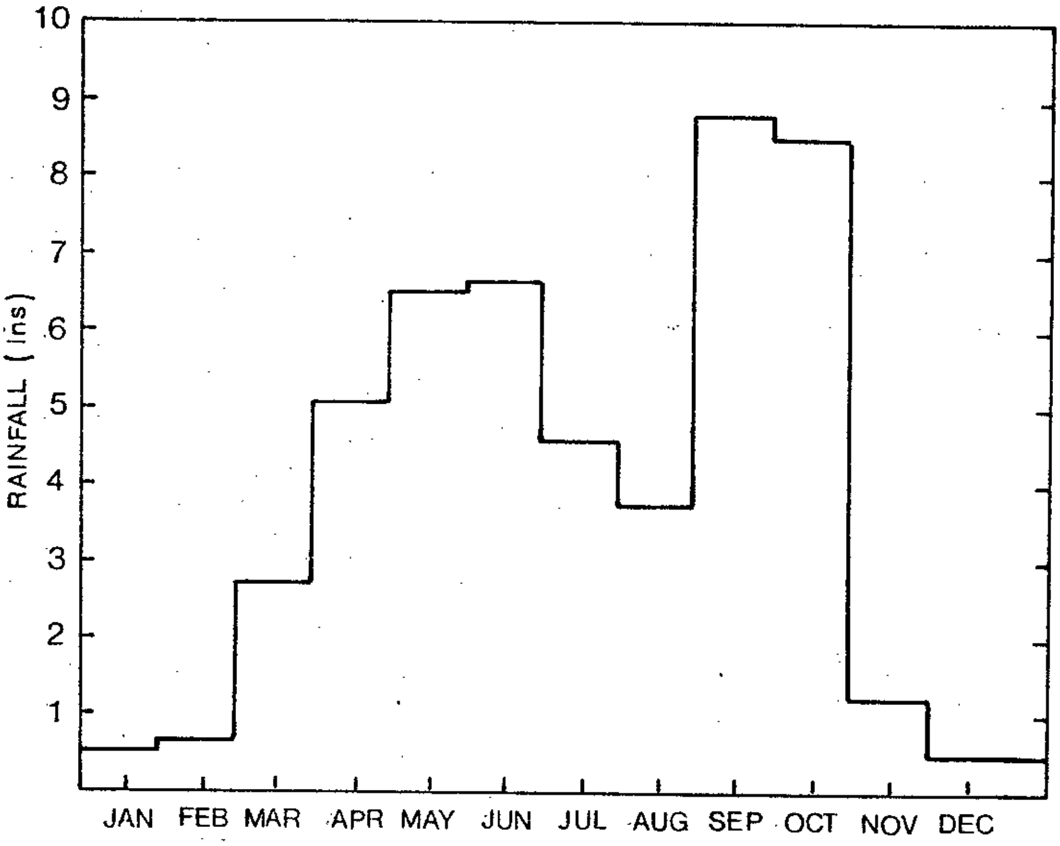

FIG. 2 – DISTRIBUTION OF MONTHLY RAINFALL: OFFA RAILWAY STATION (1946 to 1965)

runoff occurs only during the months June to January, a pattern that is consistent with the behaviour of the Oba, Ogun and Ofiki catchments that are immediately to the west, and that are hydrologically and geologically similar to the Osin. The pattern of runoff also closely follows the rainfall distribution. During the period March to May, rainfall is generally equal to or less than the potential transpiration, consequently the soil moisture deficit of the dry season is insufficiently reduced for runoff to occur. During June and July one or more large storms will trigger runoff and since rainfall is in excess of potential transpiration through the wet season, runoff will be maintained. The abrupt end of the rains in October or early November leads to a recession in streamflow which continues until late December or January.

WATER RESOURCES

Rainfall

Daily and monthly rainfall data are available for the 21 stations shown in Table 1, which also gives the rainfall statistics for each station. The stations at Ilorin (Met.) and Offa (Railway Station) each have over 25 years of record, and are referred to as the long-term stations. The other stations have a much shorter record and there are many gaps in these records, particularly in recent years.

In general less than 10 per cent of the annual rainfall occurs between November and February. Consequently where there are gaps in the monthly data during this period, the rainfall is assumed to be zero; missing data during the remainder of the year have not been estimated.

An index of annual rainfall for the region that covers the 62 year period 1914 to 1975 has been calculated using the annual data from the two long-term stations;

The index for each station in year i is given by $I_i = R_i/\bar{R}$

where R_i is the annual rainfall

and $\bar{R}$ is the long-term station mean.

The regional index is taken as the average of the indices from the long-term stations. As the annual data showed no serial correlation and suggest that the persistence from year to year is small, the regional index can be used to adjust the mean annual rainfall at each of the short-term stations. The adjusted means are given in Table 1 and shown against the station locations in Figure 3.

The isohyets show evidence of a strong regional pattern with areas of higher rainfall occurring over the high ground at the south eastern part of

TABLE 1 Rainfall Stations and Rainfall Statistics

Station		Altitude (M)	Altitude (ft)	Latitude (°N)	Longitude (°E)	Years of Record	Mean Annual Rainfall (from record) (mm)	Mean Annual Rainfall (from record) (in)	Standard Deviation (mm)	Standard Deviation (in)	Coeff. of variation (%)	Mean Annual Rainfall (adjusted)[2] (mm)	Mean Annual Rainfall (adjusted)[2] (in)
ILORIN	Met	304.8	(1000)	8 29	4 35	60	1286	(50.63)	236	(9.29)	18	1286	(50.63)
ILORIN	Government Farm	304.8	(1000)	8 30	4 35	28	1308	(51.51)	249	(9.80)	19	1255	(49.42)
ILORIN	Water Works	320.0	(1050)	8 28	4 35	17	1296	(51.02)	291	(11.45)	22	1277	(50.27)
ILORIN	Aerodrome	335.3	(1100)	8 27	4 30	9	1280	(50.39)	260	(10.24)	|20|	1219	(47.99)
IGBAJA	N.A. School	396.2	(1300)	8 23	4 53	10	1330	(52.35)	219	(8.62)	17	1316	(51.82)
OFFA	Railway Station	435.6	(1429)	8 09	4 43	56	1245	(49.00)	266	(10.46)	21	1245	(49.00)
OMUARAN	St Paul's School	518.2	(1700)	8 09	5 07	11	1523	(60.15)	402	(15.82)	26	1488	(58.59)
OMUARAN	N.A. School	548.6	(1800)	8 08	5 06	11	1518	(59.75)	432	(16.99)	28	1539	(60.59)
OMUARAN		518.2	(1700)	8 09	5 06	14	1483	(58.39)	264	(10.39)	18	1513	(59.57)
ARO-AGOR	Cent. School	304.8	(1000)	8 20	5 14	9	1331	(52.39)	372	(14.66)	|28|	1343	(52.89)
OKE-ODE	S.I.M.	304.8	(1000)	8 33	5 02	12	1335	(52.54)	327	(12.86)	25	1307	(51.44)
ZAMBUFU	N.A. School	182.9	(600)	8 47	5 11	7	1187	(46.73)	307	(12.08)	|26|	1113	(43.83)
IJERO-EKITI	Grammar School	472.4	(1550)	7 48	5 04	7	1457	(57.46)	232	(9.14)	|16|	1450	(57.10)
JSHI-EKITI		579.1	(1900)	7 52	5 10	14	1414	(55.76)	278	(10.95)	20	1357	(53.42)
OSHOGBO	P.W.D.	304.8	(1000)	7 46	4 33	34	1248	(49.15)	268	(10.55)	21	1300	(51.20)
OSHOGBO EDE	Water Works	304.8	(1000)	7 46	4 26	11	1444	(56.84)	304	(11.96)	21	1349	(53.12)
OSHOGBO	Aerodrome	301.8	(990)	7 47	4 29	31	1247	(49.11)	234	(9.22)	19	1310	(51.59)
IKIRUN		365.8	(1200)	7 55	4 40	15	1457	(57.38)	312	(12.30)	21	1401	(55.17)
IMESI-ILE	Methodist School	365.8	(1200)	7 50	4 50	10	1637	(64.45)	567	(22.32)	|35|	1513	(59.58)
ILESHA	Grammar School	365.8	(1200)			21	1351	(53.20)	324	(12.76)	24	1379	(54.29)
ILESHA	Min. of Ag.	365.8	(1200)	7 38	4 45	23	1352	(53.23)	298	(11.73)	22	1371	(53.99)

Notes 1 | | indicates stations with 10, or fewer, years of record

2 Using Offa Railway Station and Ilorin Met. as index stations for rainfall.

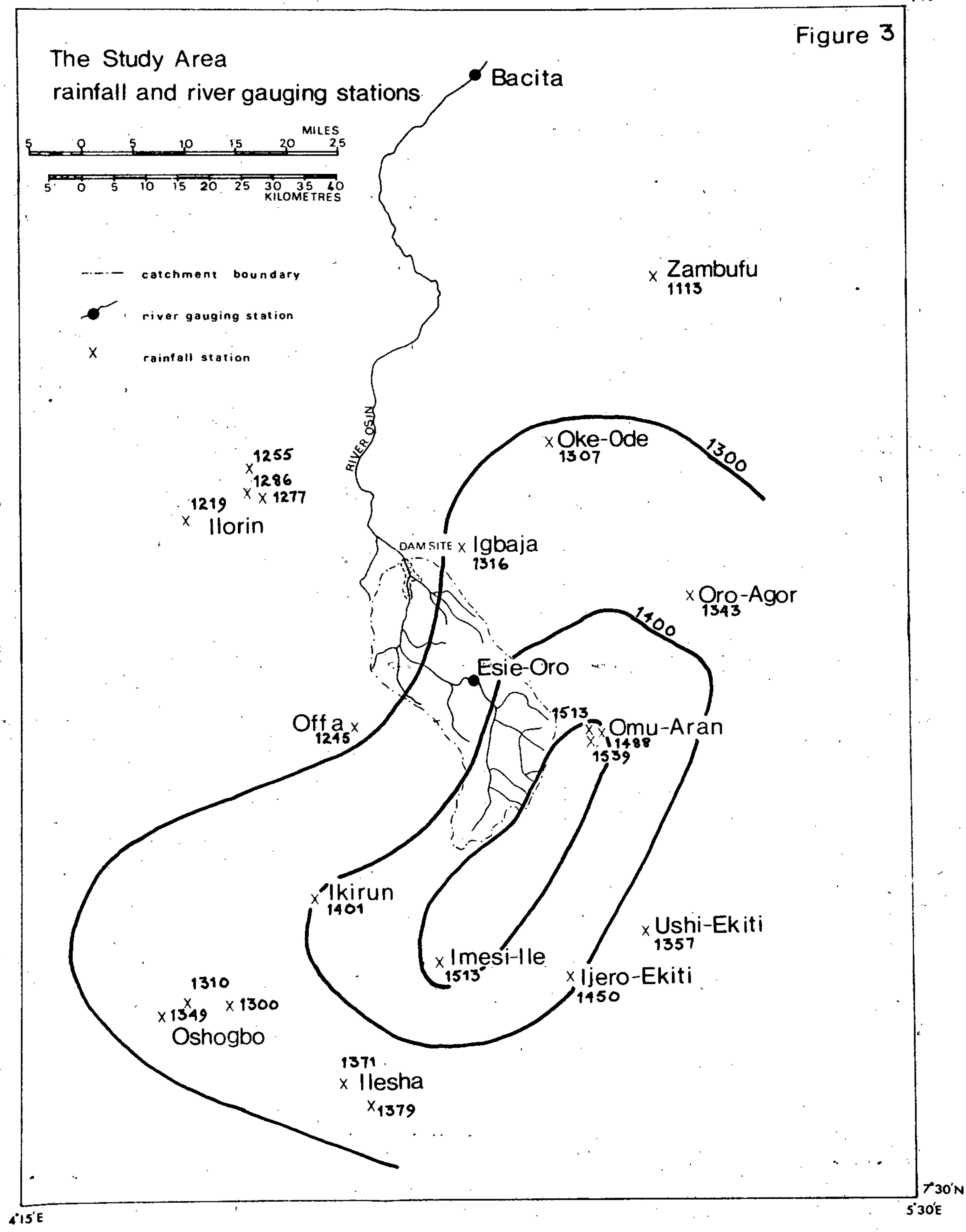
Figure 3
The Study Area
rainfall and river gauging stations
MILES
5 0 5 10 15 20 25
5 0 5 10 15 20 25 30 35 40
KILOMETRES
catchment boundary
river gauging station
rainfall station
Bacita
Zambufu
1113
RIVER OSIN
Oke-Ode
1307
1300
1255
1286
1277
1219
Ilorin
DAM SITE
Igbaja
1316
Oro-Agor
1343
1400
Esie-Oro
Offa
1245
1513
Omu-Aran
1488
1539
Ikirun
1401
Ushi-Ekiti
1357
Imesi-Ile
1513
Ijero-Ekiti
1450
1310
1349
1300
Oshogbo
1371
Ilesha
1379
7°30'N
4°15'E
5°30'E

the Esie-Oro catchment. Multiple regression analysis, with adjusted mean annual rainfall as the dependent variable and altitude, latitude and longitude as the independent variables was used to investigate this pattern. The results showed that there is a correlation between rainfall and altitude; a correlation that is not improved by the addition of either latitude, or longitude into the regression. The shape of the isohyets shown in Figure 3 therefore reflect the topography. The mean annual rainfall for the catchment areas to the Esie-Oro gauging station and Igbaja dam-site were calculated from the isohyets and are 1387 mm and 1343 mm respectively.

In order to calculate the catchment rainfall for the period for which flow data are available at Esie-Oro, we have used all the long and short-term stations to derive a best estimate of an annual index of rainfall. The annual rainfall for 1967 to 1976 is thus the product of the mean catchment rainfall (1387 mm) and the appropriate index. The basis for the extension of the runoff record of the dam site for the subsequent analysis of reservoir yield is the 62 year index of rainfall from the two long-term stations and the mean rainfall of 1343 mm for the dam-site catchment.

Runoff

River levels from daily observations of gauge boards are available for the Bacita and Esie-Oro gauging stations shown in Figure 1: the former record covers the period September 1966 to November 1976 and the latter October 1966 to October 1976. We have not used the Bacita gauge in this analysis, because a large part of its catchment is at a lower altitude than the Esie-Oro catchment and there were considerable uncertainties relating to the rating curve and the rated section. We have therefore concentrated our analysis on the Esie-Oro gauge.

The stage records at Esie-Oro appear to be reliable during the wet season, except for August and September 1969 when the daily records are identical. During the dry season, when there is negligible runoff, the river is often just a series of stagnant pools. The stage readings for this season do not seem to be consistent with this behaviour.

An approximate stage-discharge curve, based on recorded gauge heights and assumed flows is shown in Figure 4, that also shows the three available gauging results. The daily stage measurements were converted to monthly flows, using this rating curve; the results are shown in Table 2. Although the table shows a pattern of runoff consistent with our understanding of the hydrology of

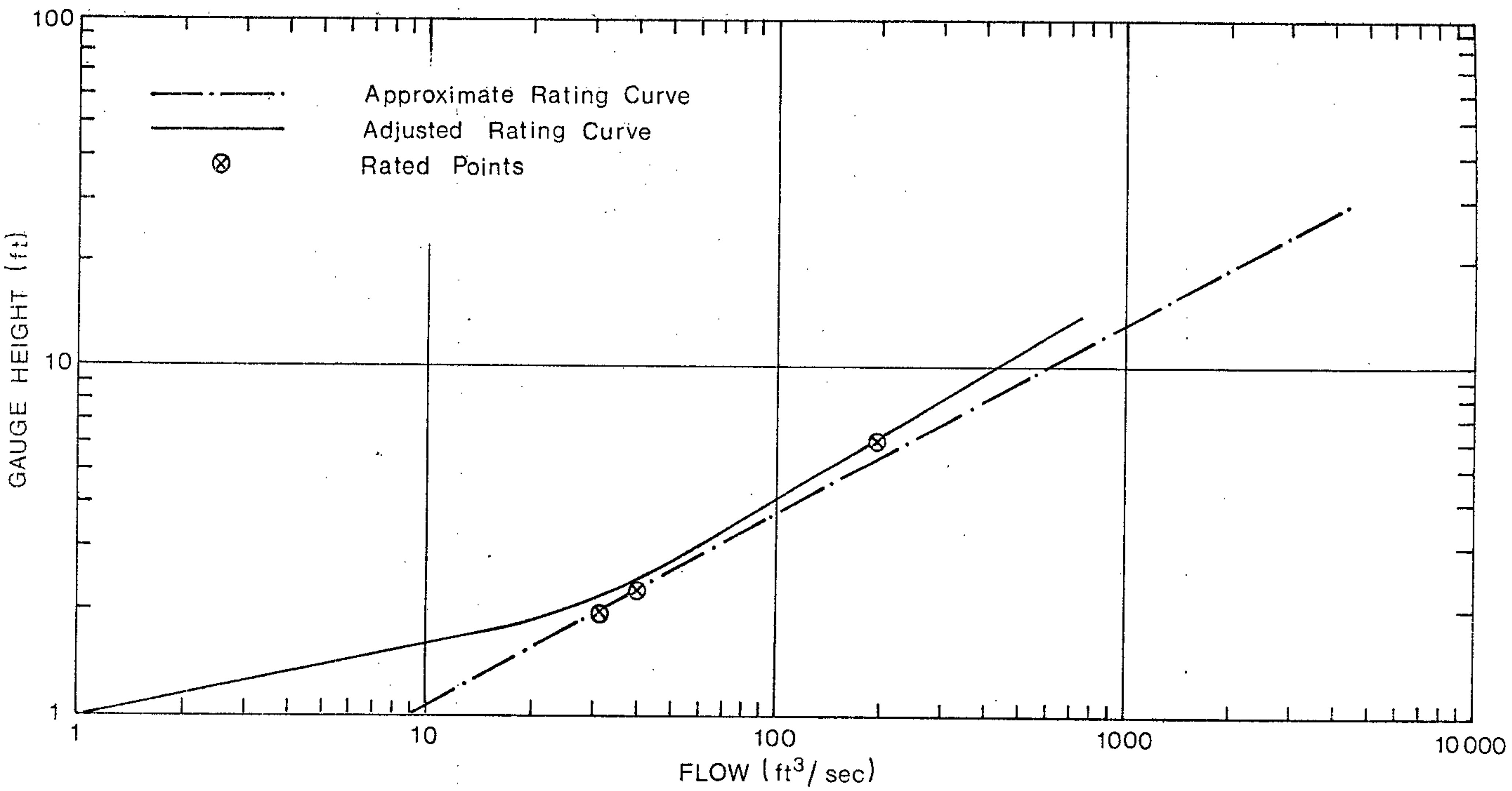

FIG. 4 – RATING CURVES

MONTHLY RUNOFF AT
ESIE-ORO
(mm)

<table>
<tr><th></th><th>J</th><th>F</th><th>M</th><th>A</th><th>M</th><th>J</th><th>J</th><th>A</th><th>S</th><th>O</th><th>N</th><th>D</th><th>Total</th></tr>
<tr><td>1967</td><td>7</td><td>4</td><td>3</td><td>5</td><td>11</td><td>13</td><td>14</td><td>7</td><td>56</td><td>66</td><td>18</td><td>9</td><td>213</td></tr>
<tr><td>1968</td><td>5</td><td>4</td><td>4</td><td>4</td><td>8</td><td>12</td><td>35</td><td>86</td><td>89</td><td>61</td><td>17</td><td>10</td><td>335</td></tr>
<tr><td>1969</td><td>7</td><td>3</td><td>4</td><td>4</td><td>8</td><td>16</td><td>35</td><td>43</td><td>43</td><td>87</td><td>58</td><td>15</td><td>320</td></tr>
<tr><td>1970</td><td>11</td><td>6</td><td>5</td><td>5</td><td>17</td><td>15</td><td>17</td><td>11</td><td>57</td><td>62</td><td>12</td><td>7</td><td>225</td></tr>
<tr><td>1971</td><td>5</td><td>3</td><td>3</td><td>2</td><td>3</td><td>9</td><td>21</td><td>16</td><td>30</td><td>61</td><td>10</td><td>7</td><td>169</td></tr>
<tr><td>1972</td><td>3</td><td>1</td><td>1</td><td>|0|</td><td>5</td><td>19</td><td>7</td><td>4</td><td>60</td><td>48</td><td>7</td><td>3</td><td>|158|</td></tr>
<tr><td>1973</td><td>2</td><td>0</td><td>0</td><td>1</td><td>0</td><td>3</td><td>5</td><td>23</td><td>48</td><td>60</td><td>21</td><td>5</td><td>168</td></tr>
<tr><td>1974</td><td>3</td><td>1</td><td>0</td><td>1</td><td>4</td><td>10</td><td>12</td><td>4</td><td>63</td><td>57</td><td></td><td>5</td><td>-</td></tr>
<tr><td>1975</td><td>2</td><td>2</td><td>3</td><td>4</td><td>11</td><td>20</td><td>40</td><td>20</td><td>16</td><td>65</td><td>14</td><td>9</td><td>204</td></tr>
<tr><td>1976</td><td>4</td><td>3</td><td>3</td><td>3</td><td>13</td><td>22</td><td>11</td><td>10</td><td>25</td><td>148</td><td></td><td></td><td></td></tr>
</table>

Note: 1) Some inconsistencies may result from rounding to the nearest millimetre.

2) | | estimated total.

the area, the low season flows are higher than we would have expected. Consequently we have constructed an alternative rating curve, also shown in Figure 4, in an attempt to reduce the dry season runoff. The change in slope of the curve for stages less than two feet is a common feature of natural rated sections at low flows. This curve passes close to the three rated points, and as individual ratings generally are scattered around a given rating, this revision is plausible. As a result of the recent bridge construction at the gauging site the original rated section has been altered. Consequently any discharge measurements that might have been made since then will not be compatible with the original stage records. Furthermore it has been impossible to check the rating curves theoretically due to the lack of both relevant topographic information and sufficient data from the individual ratings. Table 3 gives the runoff calculated from the revised rating; the results are lower than those in Table 2 and agree more closely with our understanding of the hydrology and climate of the study area.

Evaporation

Estimates of open water evaporation have been derived by Penman's method using data from the meteorological station at the University of Ibadan. The mean monthly values from the 20 years of record are shown in Table 4. The variability from year to year is small and our understanding of the climate of this part of Nigeria suggests that the Ibadan values can be applied to the Igbaja region, as it is unlikely that there are significant differences across the study area. Potential transpiration from the vegetation is taken to be 80 per cent of open water evaporation.

The relationship between rainfall and runoff

The estimated values of the annual runoff at Esie-Oro given in Table 3, and are plotted in Figure 5 against the calculated catchment rainfall. A linear regression analysis gave a correlation coefficient (r) of 0.73. In an attempt to improve the correlation we examined the effect of using wet season (June to December) runoff in order to remove the uncertainties in the rating at low flows. A poor correlation between wet season rainfall and wet season runoff was obtained. A better correlation was obtained using wet season runoff and annual rainfall and gave the following relationship that is also shown in Figure 5:

$$Q' = .158R - 67 \quad (r = .81)$$

where Q' is the wet season runoff in mm,

R is the annual rainfall in mm,

and r is the correlation coefficient.

TABLE 3

MONTHLY RUNOFF AT
ESIE-ORO
ADJUSTED RATING (mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1967	4	2	2	2	9	11	10	4	41	50	15	5	155
1968	2	1	1	2	6	10	28	63	65	48	13	8	247
1969	3	1	1	1	2	12	29	31	31	64	45	11	231
1970	7	2	1	2	12	13	15	9	43	54	10	5	173
1971	3	1	0	0	1	6	20	13	19	47	8	4	122
1972	1	0	0	-	3	16	7	2	47	38	5	1	|120|
1973	0	0	0	0	0	2	3	19	38	46	17	2	127
1974	0	0	0	0	2	9	10	1	48	44	-	2	-
1975	0	0	2	1	6	16	33	17	13	50	13	6	157
1976	1	1	0	1	10	19	9	7	20	104	-		-

Note: 1) Some inconsistencies may result from rounding to the nearest millimetre.

2) | | estimated total.

TABLE 4

ESTIMATES OF OPEN WATER EVAPORATION AND POTENTIAL TRANSPIRATION AT IBADAN

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Open water evaporation	129	150	159	150	147	126	110	104	112	130	138	131	1585
Potential transpiration	103	120	126	120	118	101	88	83	90	104	110	105	1268

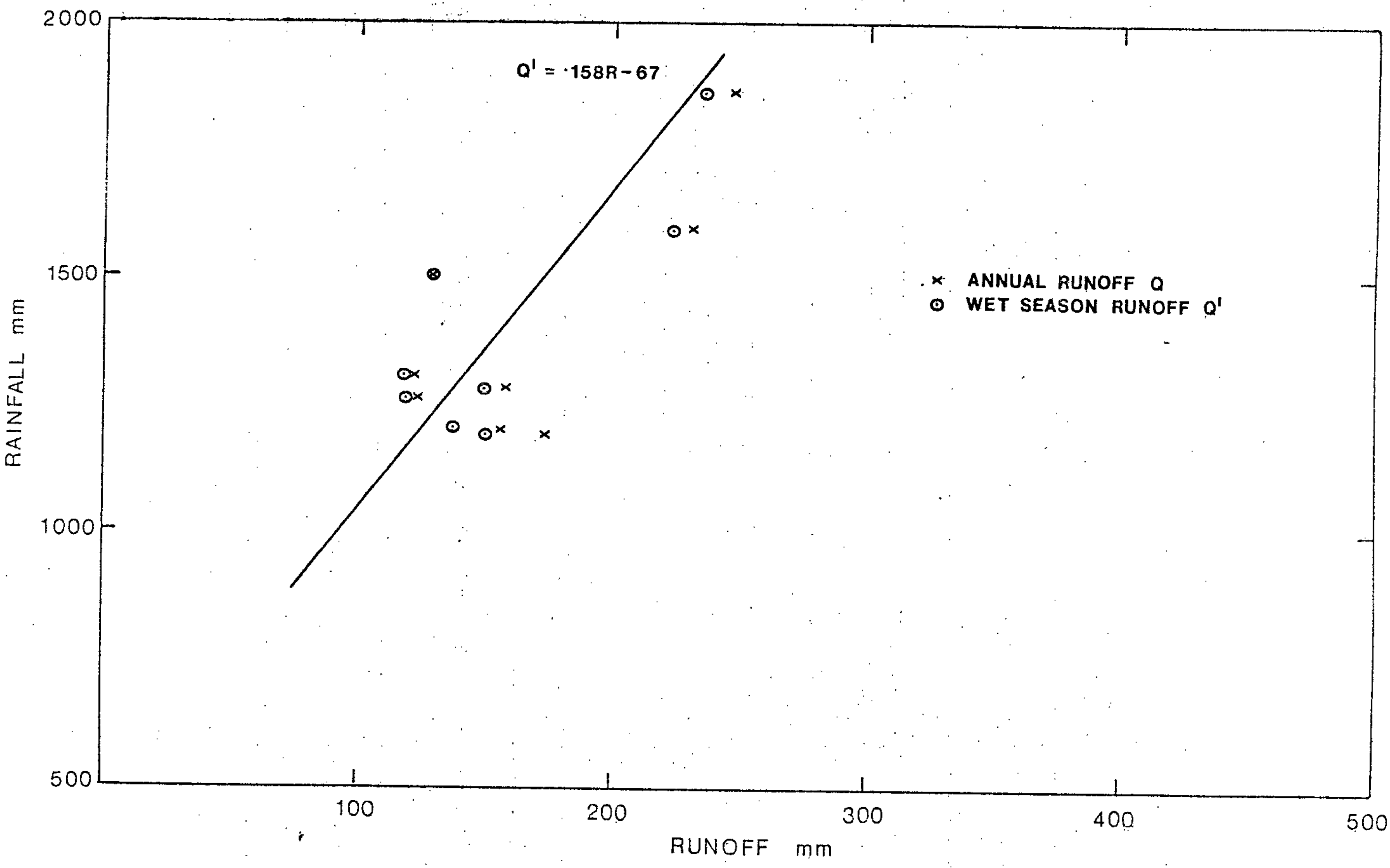

FIG. 5 - RAINFALL RUNOFF RELATIONSHIP: ESIE-ORO

This relationship is based on a very limited quantity of data. The runoff data in particular are subject to considerable uncertainties that we have been unable to resolve for the reasons given above. The equation represents the best estimate for the rainfall-runoff relationship from the data now available. While stressing the limitations of the analysis that we have been able to do, we have used the equation in order to generate a sequence of wet season flows for the reservoir yield estimation.

Estimation of reservoir yield

For the purpose of the reservoir trials we have assumed that the runoff during the dry season (January to May) is negligible. Consequently we have used the 62 year record of catchment rainfall and the regression equation for wet season runoff discussed above to calculate a sequence of annual runoff records at the dam site. An estimate of the average monthly distribution of runoff has been made from the Esie-Oro records and used with the generated series of annual flows to evaluate the monthly runoff at the dam site.

The 62 year rainfall record includes the period from 1941 to 1946 for which the average catchment rainfall was about 80 per cent of the long-term mean. This period moreover includes two consecutive years with rainfall less than 75 per cent of the long-term mean. The sequence of flows generated for the reservoir trials therefore includes a period of drought.

The reservoir operation is carried out over discrete time intervals of a month by a simple mass balance of the volume of water held in storage. The mass balance is given by:

$$S_{t+1} = S_t + Q_t - L_t$$

where S_t, S_{t+1} are the reservoir contents at the beginning and end of month t,

Q_t is the inflow,

and L_t is the release (plus losses) during the period.

The losses include evaporation from the water surface and seepage expressed as a percentage of stored volume, S_t.

The relationship between stored volume and surface area can be approximately, but conveniently expressed by:

$$A = ay^{b}$$

where A is the surface area (km^2),
V is the stored volume (million m^3),

and a and b are constants that are determined by the topography of the reservoir site. The analysis reported here is based on preliminary estimates of the reservoir characteristics.

As a result of sedimentation, a proportion of the total storage, the dead storage, is unavailable for supply. An allowance for dead storage has been made from considerations of the likely sediment yield over the design life of the reservoir. As insufficient sedimentation data are currently available, an allowance for dead storage is based on data from hydrologically similar catchments elsewhere, and has been held constant for the duration of the reservoir trials. We have assumed a sedimentation rate of 500 m^3/km^2/year that gives a dead storage of about 9.8 million m^3 over a design life of 30 years, and catchment area of 653 km^2.

We have examined the reservoir operation with the 2010 target yield of 9.0×10^6 litres/day, a dead storage of 9.8 million m^3 and zero seepage losses. As the reservoir trial is run on a monthly basis we have assumed that the target demand is equivalent to about 0.28 million m^3/month; taken from a catchment of 653 km^2 this could be derived by monthly runoff of less than half a millimetre. In contrast the average monthly runoff calculated from the 62 year record of synthetic flows is over 10 mm.

Conclusion

The following operation studies have been carried out using the proposed maximum storage volume of 28 million m^3. Based on the sequence of historic data, whose derivation is discussed above, it was found that the target demand of 0.28 million m^3/month could be met and that apart from an initial filling period no shortfalls would occur. The target demand was then raised by over a factor of ten to 3.0 million m^3/month; the results show that, allowing for a filling period of one year, shortfalls could occur in 9 months out of 732 i.e. a monthly rate of about 1%. A subsequent run indicated that a demand of 4.0 million m^3/month could be met with a monthly failure rate better than 20%. In this case however shortfalls were recorded in every year.

SPILLWAY DESIGN FLOOD ESTIMATION

Introduction

We believe that the most reliable estimate of the spillway design flood follows from the conversion of the probable maximum precipitation (PMP) to the probable maximum flood (PMF) using the unit hydrograph technique. The absence of good quality long term discharge data precludes the use of statistical methods of flood estimation and it is felt that empirical methods derived from flood data from other parts of the world are also inferior. The unit hydrograph approach allows all available local data to be incorporated into the design.

We have estimated the spillway design flood (PMF) for the proposed dam site on the river Osin at Igbaja. The data available were discussed earlier but a summary of the available data for the PMF study is given to clarify the method employed. A record of daily stage values was available from the gauging stations at Esie-Oro and Bacita from 1966 to 1976. These stations had never been adequately rated for discharge and the station of principal interest at Esie-Oro had only 3 current meter gaugings to base a curve on. The problems of rating this station were discussed earlier. Daily read raingauge records were available for various periods from a number of gauges listed in Table 1[1] and shown on Figure 1. The coverage was adequate but no gauges were actually in the catchment. Data from a recording raingauge at Ibadan University were also made available for the period 1960 to 1970 and for 1973 to 1975. The available rainfall data were analysed as described in the Met. Office Report "Extreme Rainfall in Western Nigeria" (Jackson, 1977[1]). The short duration rainfall data from Ibadan was used to complement the earlier data as a means of estimating the PMP for durations of 1 hour to 1 day.

Extensive use has been made of the techniques developed in the Flood Studies Report[2] with substitution of local Nigerian data where possible. A number of inputs are required in order to calculate a flood hydrograph by the unit hydrograph method. In this case the return period of the flood is fixed

1 Extreme Rainfalls in Western Nigeria - Jackson M.C., Met. Office 1977 Report to Scott, Wilson, Kirkpatrick & Partners.

2 Flood Studies Report in 5 Vols. - Natural Environment Research Council 1975.

as the probable maximum flood (nominally about 10^6 years). The duration of the design storm must be chosen and this determines the total storm depth from the unique depth vs duration curve for Igbaja shown later. The duration was taken as approximately two to three times the catchment lag based on Flood Studies Report findings. This rainfall must then be distributed in time according to some design profile and converted from a point rainfall to an areal value. The profile used is again based on Flood Studies Report recommendations and appropriate areal reduction factors are obtained from the Met. Office report. This design rainfall hyetograph must then be multiplied by a runoff coefficient or percentage runoff to determine the net or effective rainfall. Because no suitable detailed rainfall-runoff relationship could be developed for the study catchment, percentage runoff data from Cameroon and Togo were used. Finally this net rainfall must be combined with a unit hydrograph and a baseflow component added to yield the total flood hydrograph.

Derivation of unit hydrograph

The unit hydrograph for the dam site could not be derived in the conventional way by analysing short duration rainfall and discharge data simultaneously because the rating for Esie-Oro was so poor. In addition the rainfall is spatially and temporally very variable and it is difficult to identify a particular storm associated with any flood.

However it was possible to estimate catchment lag for Esie-Oro where this is defined as the time between the centroid of storm rainfall and the peak stage. Catchment lag is a measure of the time taken for a catchment to respond to a given rainfall input and from the Flood Studies Report can be used as an approximation to the unit hydrograph time to peak. In this case, with a daily read staff gauge and daily read raingauges of sometimes questionable validity, it is only possible to estimate lag to the nearest half day or even day for any event. However by averaging a large number of flood events it should be possible to estimate lag adequately. For each of 34 major floods over the period of records the lag was estimated from an average centroid of all operating raingauges to the peak stage. The median value of all these lags was a little under 1 day but because of the uncertainties in the method 1 day was assumed. From the Flood Studies Report the unit hydrograph time to peak (Tp) is approximated by

$$Tp = 0.9\ LAG$$

Thus Tp is approximately 22 hours.

It is possible to estimate Tp from mainstream length (L), slope (SL1085) and a short duration rainfall index (RSMD) which is the 1 day rainfall of 5 year return period minus average soil moisture deficit (SMD), using a regression equation developed for the Flood Studies Report:

$$Tp = 46.6\ L^{0.14}\ SL1085^{-0.38}\ RSMD^{-0.4}$$

For Esie-Oro this yields a value of 8.7 hours for a 1 hour 10 mm unit hydrograph. For a 1 day storm this Tp value is adjusted following Flood Studies report findings as:

$$T_{p24\ hours} = T_{p1\ hour} + \left(\frac{24-1}{2}\right)$$

$$= 20.2\ \text{hours.}$$

From the two methods it seems appropriate to use a Tp value of 21 hours for a 1 day storm. Whilst using a regression equation developed from United Kingdom data in Nigeria is questionable, because the equation is physically based and relies largely on length and slope to determine Tp, it is probably a valid indicator of Tp, and a useful check on the earlier method based on catchment lag.

In order to estimate Tp for the proposed dam site from that for Esie-Oro the ratio of stream length/$\sqrt{\text{slope}}$ for each site was used. The Tp for the Igbaja dam site is thus 40 hours.

This time to peak of 40 hours for the proposed gauging station is for a 1 day storm which is assumed to have a duration of about 18 hours. This figure of 18 hours was assumed by the Meteorological Office in their report "not because 1 day falls in Nigeria are as long lasting as this, but because it is suspected that some of the stations have been measuring accumulations of rainfall over alternate days during parts of their record". Thus the assumed Time to peak for the damsite for a 10 mm in 18 hour storm is 40 hours. It is appropriate to choose a shorter time interval than this however in order to obtain accurate resolution of hydrograph peaks and a time interval of 6 hours was used. Then from the Floods Studies Report once more we find that:

$$T_{p\ 6\ hrs} = T_{p\ 18\ hrs} + \left(\frac{1-6}{2}\right)\ \text{hours}$$

$$= 37.5\ \text{hours}$$

This was rounded down to 37 hours because of the poor data.

A simple triangular unit hydrograph was derived from this single parameter Tp where the peak discharge (Qp) is given by

$$Qp = \frac{220}{T_p} \text{ cumecs/100 km}^2$$

The time base (TB) is given as

$$TB = 2.52 \text{ Tp hours}$$

Both relationships were developed for the Flood Studies Report and give the unit hydrograph shown in Figure 6.

Percentage runoff

It was next necessary to decide how much of the gross rainfall would be effective in producing rapid response runoff, (surface or near surface flow) rather than subsurface baseflow. Little published data were available but data from Cameroon to the east and Togo to the west were available from ORSTOM[1]. On small representative basins of similar geology (Pre-Cambrian basement complex) and soils (tropical soils with ferruginous concretions of sands and gravels) a percentage runoff of 35 to 45 per cent is common for Togo. For Cameroon 20-50 per cent is observed. These areas of Togo and Cameroon are obviously rather different to Western Nigeria but since they have similar climates (as shown by mean annual rainfalls, rainfall distributions and temperature data from ORSTOM), the percentage runoffs quoted for these annual floods will be a good first approximation to the standard percentage runoff (SPR) component of the Flood Studies Report prediction technique:

$$PR = SPR + 0.22\ (CWI-125) + 0.1\ (P-10)$$

where SPR = standard percentage runoff (produced by 10 mm of rain on the catchment under standard antecedent conditions of zero soil moisture deficit and zero antecedent precipitation during previous days);

CWI = catchment wetness index, an index of the antecedent state of the catchments;

P = total storm rainfall.

[1] Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) Recueil des données de base de Bassins Representatifs et Experimentaux Paris 1971. Vols. 1 and 2.

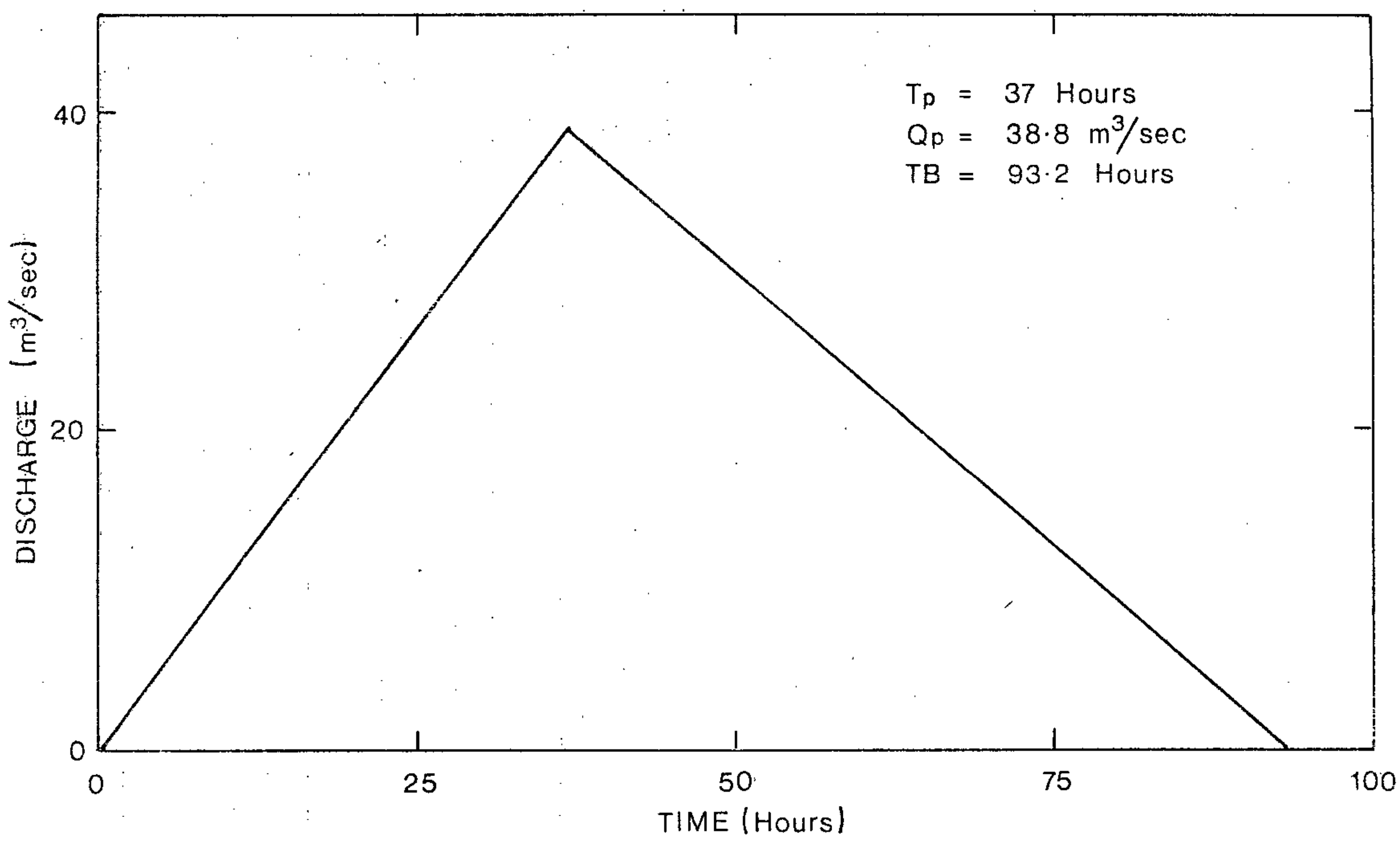

FIG. 6 — UNIT HYDROGRAPH FOR DAM SITE

This standard percentage runoff is increased by the contributions from CWI and storm rainfall so that greater percentage runoffs are experienced for large storms on wet catchments.

Based on the ORSTOM data an SPR of 40 per cent was chosen for Igbaja. In the cases studied here percentage runoffs were just less than 100 per cent, which although it is rather severe is thought to be appropriate.

Design rainfall

A choice of duration and time distribution of the rainfall or rain profile must be made to specify the design storm. The return period is the PMP (nominally 10^6 years) and once the duration is determined, the depth follows from the curve (Figure 11 in the Meteorological Office Report) which gives the rainfall depth for any duration at any point in the catchment. An areal reduction factor from their Figure 9 must be applied to get the measure of areal rainfall which is given in Table 21 of their report.

An areal rainfall depth duration curve for the catchment was plotted from Figures 9 and 11, and Table 21 of the Meteorological Office report and is shown here as our Figure 7.

We considered that a duration of approximately 2 to 3 times the unit hydrograph time to peak would be appropriate but various durations were tried to test this. Durations of 66, 102 and 138 hours were studied (corresponding to approximately 3, 4 and 6 days respectively). In fact as we show later the choice of duration is relatively unimportant in view of the rainfall profile that was chosen. Whilst some comments on the distribution of the rainfall in time (the rainfall profile) were given by the Meteorological Office, we considered that a more extreme, peakier profile should be used for the PMP case. We chose a nested profile whereby the PMP for all durations should occur in the same storm; that is, the PMP 1 hour fall should occur at the centre of the PMP 3 hour fall within the PMP 5 hour fall and so on. In this way a symmetrical rain profile was built up from the depth duration diagram of Figure 7 for the durations chosen, which were all odd multiples of 6 hours, the unit hydrograph time interval chosen. This produces a very severe profile that maximises the flood peak. This technique is recommended for use in the United Kingdom and so has been used here.

Catchment wetness index

Some index of the antecedent state of the catchment prior to the design

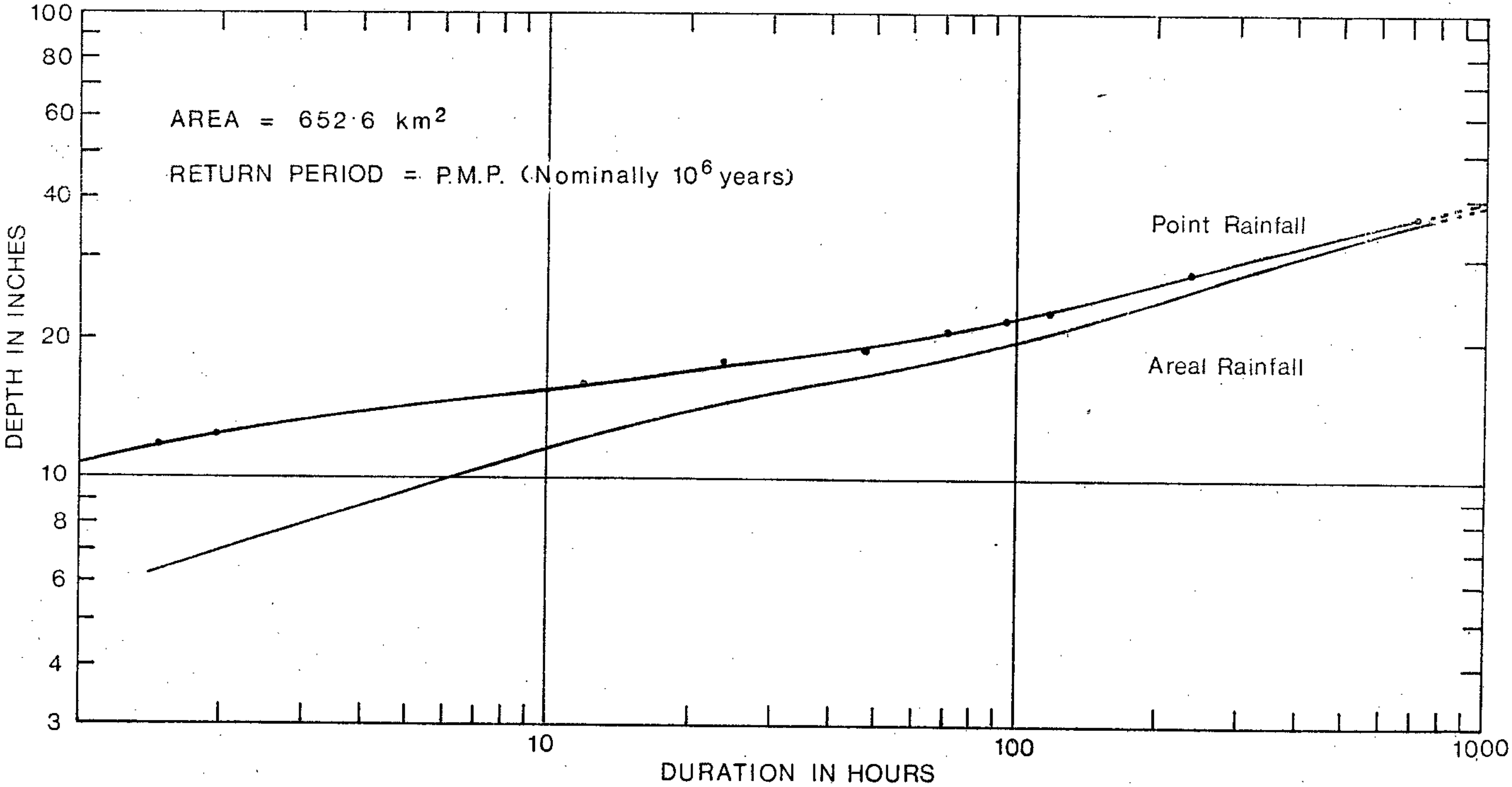

FIG. 7 — RAINFALL DEPTH DURATION CURVE FOR IGBAJA DAM CATCHMENT

storm was required and we used the Catchment Wetness Index (CWI) from the Flood Studies Report. This index is a combination of the soil moisture deficit (SMD = cumulative gross rainfall minus evaporation) and a 5 day antecedent precipitation index (API5) such that

$$CWI = 125 - SMD + API5$$

The constant 125 is added simply to maintain positive CWI values since in the United Kingdom SMD rarely exceeds 125. In fact in Western Nigeria during the wet season there will be no soil moisture deficit and the CWI reduces to

$$CWI = 125 + API5$$

The Flood Studies Report was again used to estimate the API5. It was assumed that the PMP rain profile extended for 5 x D, where D is the chosen design duration, and that half the difference between this 5 x D and the design duration D fell uniformly in 2 x D hours prior to the design storm. Thus CWI is dependent on the design duration D.

Baseflow

The convolution of the unit hydrograph with net rainfall gives the rapid response component of the total hydrograph. To this must be added a slow response baseflow component of the hydrograph. This was approached in a number of ways.

Firstly the Flood Studies Report gives a prediction equation using the catchment wetness index described above plus a net 1 day rainfall of 5 year return period (RSMD). The baseflow or average non-separated flow (ANSF) is given as

$$ANSF = AREA\ (0.000326\ (CWI-125) + 0.00074\ RSMD + 0.003)\ \text{cumecs}$$

RSMD was calculated from the Meteorological Office report and the values of CWI computed earlier were used. The results are given in Table 12. The baseflow is assumed to be uniform throughout the flood.

Secondly, in order to check this figure, the average wet season flow was examined since it was assumed that the most severe PMF would follow from the PMP falling on the catchment during an already high wet season flood which would provide the baseflow component of the PMF. The average wet season flood for Esie-Oro was 12.6 cumecs and this was adjusted by the ratio of catchment areas to give the estimated baseflow at the dam site. This figure of 27.1 cumecs can be compared with the first estimates of baseflow given in Table 5 and it can be seen that these first estimates based on the Flood Studies Report appear rather high. Thus a revised weighting of 0.00037 RSMD was used in order to give adjusted ANSF values that were in better agreement with the wet season discharges and are shown in Table 5. Baseflow is relatively unimportant in the total calculation and so this adjustment seems appropriate.

Results of rainfall runoff convolution

The various design storms discussed above were multiplied by appropriate percentage runoffs (which ranged from 87.5 to 95.5 per cent finally) and convoluted with the unit hydrograph. It should be noted that the chosen "standard" percentage runoff of 40 per cent was increased by the contribution from CWI and the storm rainfall, P. The results for various durations are given in Table 6A, 6B and 6C.

It can be seen that increasing the design duration from 66 hours (nominally 3 days) to 138 hours (nominally 6 days) only increases the peak from 1349 cumecs to 1498 cumecs (11%). Thus the increasing volume of rainfall in the longer durations is partially offset by a decreasing percentage runoff since CWI decreases. In fact the peak is largely determined by the peak rainfall intensity since the rain profile is such a severe, peaky shape and increasing the duration serves only to add slightly to the shoulders of the storm.

We recommend that a duration of 138 hours be used which yields a flood peak of 1498 cumecs. The 6 hourly ordinates of the hydrographs for all 3 durations are given in Tables 6A 6B and 6C for reservoir routing studies in order to obtain the spillway design flood. Such routing has not been attempted here since no data on likely stage discharge relationships for the proposed spillway nor storage stage relationships are available.

Conclusions and recommendations

We believe that the recommended design flood with a peak of about 1500 cumecs is the best estimate that can be made at present. A number of assumptions have had to be made about catchment lag, antecedent conditions, storm duration and percentage runoff.

BASEFLOW COMPUTATIONS

Catchment Area to Esie-Oro = 303 km^2
Catchment Area to proposed dam = 653 km^2

Storm Duration (hours)	RSMD (mm)	CWI (mm)	ANSF (m^3/sec)	Adjusted ANSF (m^3/sec)
66	81	145	45.5	24.0
102	81	133	42.9	21.4
138	81	128	41.9	20.4

Estimated maximum wet season
discharge at dam site (m^3/sec) 27.1

TABLE 6A

IGBAJA DAM SITE P M F COMPUTATIONS

DURATION=66 HOURS

AREA (SQ.KM.)	652.6
DATA INTERVAL (HR)	6.0
DESIGN DURATION (HR)	66.0
TOTAL RAIN (MM)	452.0
PERCENTAGE RUNOFF	87.5
ANSF (CUMECS PER SQ.KM.)	.08
CWI AT START OF STORM	143.[illegible]

TRIANGULAR UNIT HYDROGRAPH COMPUTED FROM TP= 37.0

CONVOLUTION OF UNIT HYDROGRAPH AND NET RAIN PROFILE

TIME	TOTAL RAIN MM	NET RAIN MM	UNIT HYDROGRAPH ORDINATE	TOTAL HYDROGRAPH
.00	10.20	8.92	.00	51.69
6.00	12.70	11.11	.96	57.38
12.00	12.70	11.11	1.93	69.91
18.00	19.00	16.62	2.89	89.51
24.00	55.90	48.91	3.86	119.57
30.00	231.00	202.12	4.82	186.41
36.00	55.90	48.91	5.79	368.44
42.00	19.00	16.62	5.42	579.50
48.00	12.70	11.11	4.79	789.84
54.00	12.70	11.11	4.16	995.62
60.00	10.20	8.92	3.53	1192.04
66.00			2.91	1348.78
72.00			2.27	1321.78
78.00			1.64	1217.32
84.00			1.01	1089.95
90.00			.38	955.67
96.00				800.69
102.00				644.48
108.00				491.88
114.00				344.76
120.00				209.76
126.00				119.98
132.00				88.23
138.00				71.31
144.00				60.31
150.00				53.89

TABLE 6B

IGBAJA DAM SITE P M F COMPUTATIONS

DURATION=102 HOURS

AREA (SQ.KM.)	652.6
DATA INTERVAL (HR)	6.0
DESIGN DURATION (HR)	102.0
TOTAL RAIN (MM)	512.8
PERCENTAGE RUNOFF	92.1
ANSF (CUMECS PER SQ.KM.)	.08
CWI AT START OF STORM	133.4

UNIT HYDROGRAPH USED FROM PREVIOUS CASE (SEE ABOVE)

CONVOLUTION OF UNIT HYDROGRAPH AND NET RAIN PROFILE

TIME	TOTAL RAIN MM	NET RAIN MM	UNIT HYDROGRAPH ORDINATE	TOTAL HYDROGRAPH
.00	10.10	9.30	.00	50.26
6.00	10.10	9.30	.96	56.12
12.00	10.20	9.40	1.93	67.83
15.00	10.20	9.40	2.89	85.45
24.00	12.70	11.70	3.86	108.99
30.00	12.70	11.70	4.82	139.89
36.00	19.00	17.50	5.79	178.15
42.00	55.90	51.50	5.42	219.36
48.00	231.00	212.82	4.79	283.29
54.00	55.90	51.50	4.16	471.37
61.00	19.00	17.50	3.53	682.08
66.00	12.70	11.70	2.90	892.03
72.00	12.70	11.70	2.27	1097.16
78.00	10.20	9.40	1.64	1292.46
84.00	10.20	9.40	1.01	1445.97
90.00	10.10	9.30	.38	1411.94
95.00	10.10	9.30		1373.72
102.00				1181.08
108.00				1049.10
114.00				938.31
120.00				762.58
126.00				611.39
132.00				456.26
138.00				314.22
144.00				198.18
151.00				153.23
156.00				123.89
162.00				100.83
168.00				82.52
174.00				68.68
180.00				58.70
186.00				52.57

TABLE 6C

IGBAJA DAM SITE P M F COMPUTATIONS

DURATION=138 HOURS

AREA (SQ.KM.)	552.6
DATA INTERVAL (HR)	6.0
DESIGN DURATION (HR)	138.0
TOTAL RAIN-(MM)	558.4
PERCENTAGE RUNOFF	95.5
ANSF (CUMECS PER SQ.KM.)	.03
CWI AT START OF STORM	128.2

UNIT HYDROGRAPH USED FROM PREVIOUS CASE (SEE ABOVE)

CONVOLUTION OF UNIT HYDROGRAPH AND NET RAIN PROFILE

TIME	TOTAL RAIN MM	NET RAIN MM	UNIT HYDROGRAPH ORDINATE	TOTAL HYDROGRAPH
.00	7.60	7.26	.00	49.14
6.00	7.60	7.26	.95	53.71
12.00	7.60	7.26	1.93	62.85
18.00	10.10	9.65	2.89	76.56
24.00	10.10	9.65	3.86	96.34
30.00	10.20	9.75	4.82	122.19
36.00	10.20	9.75	5.79	154.17
42.00	12.70	12.13	5.42	185.99
48.00	12.70	12.13	4.79	217.89
54.00	19.00	18.15	4.16	249.87
60.00	55.90	53.41	3.53	283.65
66.00	231.00	220.71	2.90	341.99
72.00	55.90	53.41	2.27	527.69
78.00	19.00	18.15	1.64	736.65
84.00	12.70	12.13	1.01	945.43
90.00	12.70	12.13	.38	1149.21
96.00	10.20	9.75		1343.97
102.00	10.20	9.75		1498.46
108.00	10.10	9.65		1461.31
114.00	10.10	9.55		1349.08
120.00	7.60	7.26		1221.69
126.00	7.60	7.25		1089.58
132.00	7.60	7.26		953.23
138.00				815.29
144.00				672.20
150.00				525.03
156.00				381.06
162.00				278.49
168.00				231.73
174.00				193.65
180.00				160.70
186.00				132.78
192.00				109.46
198.00				91.16
204.00				74.84
210.00				63.49
216.00				55.72
222.00				50.94

However, such assumptions have been made following examination of all presently available local data.

We recommend that during the period from the presentation of this report to dam construction, additional rainfall data and flow data should be collected. In particular a recording river level gauge should be installed upstream of the proposed reservoir site to enable better estimates of catchment lag to be made. If the section could be rated to give more reliable discharge estimates this would provide a check on the assumptions that led to the estimates of reservoir yield. In addition the installation of some raingauges in the dam-site catchment should give results that would enable unit hydrographs to be derived in the conventional way.

We believe that such a programme of data collection is vitally important and that the costs incurred would be very small in comparison to the total scheme costs.